WHEELER

Thermal Conductivity of Concrete

Civil Engineering

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THERMAL CONDUCTIVITY OF CONCRETE

BY

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THESIS

FOR THE

DEGREE OF

BACHELOR OF SCIENCE

IN

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IN THE

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I recommend that the thesis prepared under my supervision by ARTHUR WAYNE WHEELER entitled Thermal Conductivity of Concrete be approved as fulfilling this part of the requirements for the degree of Bachelor of Science in Civil Engineering.

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THERMAL CONDUCTIVITY OF CONCRETE.

INTRODUCTION.

The use of concrete for bridge and building purposes has become so general that much investigation of the various properties of this material has been carried on for a number of years. Some of the properties of concrete, such as strength and permeability by water, have been given much attention, while others have been studied but little. One of the things that has not been the subject of exhaustive investigation is the rate with which concrete conducts or transmits heat. However, some study has been given to this property and experiments have been made by various methods. Mr. L. A. Waterbury wrote a thesis at the University of Illinois in 1905 on the "Thermal Properties of Concrete", giving the results of his own experiments. Prof. Ira H. Woolson has conducted a series of experiments, the results of which were published in Vols. 6 and 7 of the Proceedings of the American Society for Testing Materials under the title, "Investigation of the Thermal Conductivity and Effect of Heat upon the Strength and Elastic Properties of Concrete." A more recent set of experiments and those dealing directly with the thermal capacity of concrete was made by Prof. C. L. Norton. The results of these experiments were published in the Engineering News, Vol. 64, page 711.

The importance of this subject has become greater in the last few years, as the concrete structure has gradually

replaced the wood and steel construction. Little is known of the internal stresses set up in a mass of concrete by atmospheric variations in temperature. On account of the lack of uniformity of results of previous experiments, a series of tests somewhat similar to those conducted by Mr. Waterbury was undertaken by the writer.

DEFINITIONS.

Before proceeding with the explanation of the method and results, certain definitions are necessary.

In order to define the thermal conductivity of a substance, assume that a slab of the material with equal parallel faces A_1 and A_2, d units distance apart, has a temperature of t_1 at the A_1 face and t_2 at the A_2 face. The heat will pass from one face toward the other. In a definite time T, Q units of heat will have transmitted through the slab.

$Q = \frac{k\ T\ A\ (t_1 - t_2)}{d}$, where k is a constant depending on the nature of the solid. This constant is independent of A, the area of the parallel faces, d, the distance between the faces, T, the time of heating, and $t_1 - t_2$, the difference in temperature. If A, d, T, and $t_1 - t_2$ are each unity, k is the quantity of heat that is transmitted through the slab, and this quantity is called the thermal conductivity of the substance.

The rate with which a body decreases or increases in temperature depends upon the specific heat of the material. Specific heat is the quantity of heat necessary to raise one gram of a substance through one degree Centigrade at a given temperature.

By one method of determining the thermal conductivity of a solid, a prism of the material is heated on the end and temperature readings taken at intervals throughout its length. A temperature-distance curve is then drawn so that the scales of temperatures and distances are the same. The ordinates of the curve represent temperatures corresponding to distances from the heated surface as abscissas. On the temperature-distance curve, consider any two sections of the body which are an infinitesimal distance apart, say, dx: the difference in temperature of the two faces is given by dt. A straight line passing through the corresponding points of the curve forms an angle B with the axis of abscissas. The tangent of this angle is $\frac{dt}{dx}$, since the scales for temperatures and distances are the same. The quantity $\frac{dt}{dx}$ is otherwise known as the temperature gradient or the rate of change of temperature for the sections under consideration. If $dt = t_1 - t_2$, and $dx = d$ where

t_1= temperature of face nearest source of heat,

t_2= temperature of face farthest from source of heat,

d = distance between the faces,

$$\tan B = \frac{dt}{dx} = \frac{t_1 - t_2}{d}; \qquad (1)$$

since

$$Q = \frac{k\ T\ A\ (t_1 - t_2)}{d}, \qquad (2)$$

and if T is equal to unity,

$$Q = k\ A \tan B; \qquad (3)$$

in which Q is the quantity of heat transmitted in a unit of time through section A where tan B is measured.

DESCRIPTION OF TESTS.

The material used throughout the tests was a 1 : 3 : 6 mixture of broken limestone concrete. It was mixed wet enough that the mass quaked slightly after thorough tamping.

Holes for the mercury thermometers were made in the specimens by molding three-eighths inch iron rods into them and removing the rods after the concrete had set. Each of the test pieces was stored in wet sand for a period of thirty days and allowed an additional thirty days in a dry place to complete the seasoning. At the end of sixty days, specific heat and conductivity tests were made.

The determination of the specific heat of the concrete was made by the calorimeter method. Special care was taken to transfer the heated concrete quickly to the calorimeter. The data and results of this test are shown on page 20.The results were calculated from the following formula.

$$S = \frac{W\ (t_3 - t_2)}{M\ (t_1 - t_3)}\ , \qquad (4)$$

where

S = the specific heat of the substance,

W = the weight of the water used in calorimeter in grams,

M = the weight of concrete used,

t_1 = the initial temperature of the concrete when heated, in degrees C,

t_2 = the initial temperature of the water in degrees C,

t_3 = the final temperature of the mixture of water and concrete in degrees C.

The general method of heating the specimens in all of the thermal conductivity tests was the same, the only difference being in the matter of the shape of the specimens. Electric lamps were used as a source of heat. An attempt was made to arrange them in such a manner that the exposed surface of the concrete should have a fairly uniform temperature. On the sides of the test pieces that were unexposed to the lamps, a packing of mineral wool was used in order to reduce the amount of radiation as much as possible. In order to prevent radiation from the thermometer holes, a casing of asbestos paper was made for each of the holes and the thermometer was fitted closely in this casing.

The first test was made on a concrete beam one foot square and three feet long, the heat being applied as shown in the diagram on page 13.The beam was surrounded with two and one-half inches of tightly packed mineral wool to prevent radiation. The temperatures were taken at the center of the beam at intervals of four inches for its entire length. The temperature readings and the time elapsed between readings are shown in Table 1, page 15.It required fifteen hours for the heat to pass through the entire length of the beam, but from the readings of thermometers imbedded in the mineral wool adjacent to the beam, the amount of radiation from the center would seem inappreciable. Although the beam was very warm, the mineral wool packing showed only a slight increase in temperature an inch from the concrete.

The second test was made on a solid concrete cylinder sixteen inches in diameter and twenty-two inches high. The heat

was applied around the circumference of a central section of the cylinder. The thermometers were placed in holes at the ends as shown by the diagram on page 14.On account of the thinness of the concrete between adjacent thermometers, readings were taken oftener than in the beam test. The test was continued for some time after the center thermometer had shown a rise of temperature. This test was made when the specimen was sixty days old; the third and fourth tests were made on the same cylinder in the same manner as described above at seventy and seventy-three days respectively.

The fifth and last test was made on a solid cylinder sixteen inches in diameter and sixteen inches high. The ends of the cylinder were left open to the circulation of the heated air of the box. The space around the thermometers where they projected from the concrete, was packed with mineral wool to prevent their being influenced by the heated air near the end of the cylinder.

In each of the experiments it was found necessary to remove the thermometers partially from their positions in the specimens in order to read the temperatures. By experiment, it was found that an appreciable drop in temperature was not observed until four or five seconds had elapsed. The maximum time required for reading any thermometer was three seconds.

COMPUTATIONS.

On account of the difference in shape of the sections of concrete under consideration in the beam and the cylinder, different equations were necessary in the computation of the

thermal conductivity. In the case of the beam, consider any two unit sections A_1 and A_2 at the axis of the beam, l centimeters apart. As indicated by the temperature-distance curve there is a rise in temperature throughout the length l between A_1 and A_2. Then the product of the average rise in temperature, the length between the two sections, and the specific heat will give the quantity of heat which the prism of unit cross section has received in the time T, that is,

$$q = S\ (t_1' - t_2')\ l \qquad (5)$$

If the entire length of the beam be considered divided into a number of equal prisms of length l, the total quantity of heat which the concrete has absorbed will be a summation of the products of the lengths, their corresponding average rise in temperature for the time T, and the specific heat. Or,

$$Q = S\ (t_1 - t_2)\ L \qquad (6)$$

where

Q = the total quantity of heat,

$t_1 - t_2$ = the average rise in temperature for the length of the beam L.

Also since

$$Q = k\ T\ A\ \tan B, \qquad (3)$$

equating (6) and (3) and solving for k, assuming A as unity,

$$k = \frac{S\ (t_1 - t_2)\ L}{T \tan B}, \qquad (7)$$

where

k = the thermal conductivity of the concrete, as already defined,

tan B = the temperature gradient, which is the average value for two adjacent temperature-distance curves,

T = the time elapsed between initial and final temperature readings.

It will be seen that for the beam, when the temperature-distance curve is drawn so that one vertical division is equal to one degree and one horizontal division is equal to one centimeter, the value of the temperature gradient can be scaled directly for the points under consideration. and that the area to the right of the section A between two adjacent temperature-distance curves, multiplied by the specific heat of the concrete, is the quantity of heat which passes any section A in the corresponding time. The quantities of heat were obtained both by the use of the polar planimeter and by scaling the temperatures directly from the curves. The results of the former only were recorded as they seemed the more accurate. By the use of the equations given previously, values of k, the thermal conductivity were calculated. Calculations were made for several sections in each set of adjacent temperature-distance curves.

The method followed in the computation of results of the cylinder tests was the same for each case. Temperature-distance curves were drawn as for the beam. The equation used in the calculations was primarily the same as for the beam test. The sections under consideration were cylindrical surfaces one centimeter high with radii varying by two and one-half centimeters. From the temperature-distance curves, the difference in temperature and the temperature gradient for each section used

in the computations were scaled. Instead of prisms of unit cross section and length l as in the case of the beam, annular rings of unit height were considered. The product of the unit height, the area between two cylindrical surfaces, the mean rise in temperature of the ring for a time T elapsed between readings for adjacent curves, and the specific heat, gave the quantity of heat which had been absorbed by the ring in a time T. That is, for a ring of unit height where $r_1 - r_2$ is very small

$$q = \pi (r_1^2 - r_2^2)(t_1 - t_2) S \qquad (8)$$

where

q = the quantity of heat which has been added to the ring between two cylindrical surfaces which are r_1 and r_2 units distant from the axis of the cylinder,

$t_1 - t_2$ = the average rise in temperature of that portion of the concrete contained in the ring, for an interval of time T.

If the section of the cylinder is divided into n number of concentric rings, then the total quantity of heat Q which has passed the cylindrical section of which r is the radius in the time T, is given by the following equation, which is a summation of the expressions for the quantities of heat that have been added to all the rings between the outside section and the center.

$$Q = \pi S \left[(r_1^2 - r_2^2)(t_1 - t_2) + (r_2^2 - r_3^2)(t_2 - t_3) + \cdots r_n^2 (t_n - t_n')\right], \qquad (9)$$

in which, t_n' is the initial temperature of the concrete at the center.

Also

$$Q = k\ T\ A \tan B = 2\ \pi\ r\ k\ T \tan B. \qquad (10)$$

Equating these two values of Q and solving for k,

$$k = \frac{\pi S \left[(r_1^2 - r_2^2)(t_1 - t_2) + (r_2^2 - r_3^2)(t_2 - t_3) + \cdots r_n^2 (t_n - t_n')\right]}{2 \pi r T \tan B} \qquad (11)$$

RESULTS.

From the nature of the experiments it is reasonable to expect that some errors may have entered which have affected the final result. Some of these errors have been partially eliminated, for example, errors in the thermometer readings due both to inaccurate thermometers and to possible error in taking each reading. Temperatures and temperature gradients which were used in the calculations were taken from a series of smooth curves which were drawn through or near the various points of each set of readings. By drawing these smooth curves through the points, if the computed quantity of heat was increased for one time interval, it was decreased for the next, and since an average value of the thermal conductivity was taken from the results obtained, the errors of observation and inaccuracy of thermometers were compensating. Radiation was another source of error that was partially eliminated by covering the exposed surface with a good non-conductor of heat. However, this error is the most uncertain and it is impossible to eliminate it completely by the method followed in this set of experiments. There was of course, some inaccuracy in measuring distances. In spite of the precaution taken to have the heat applied uniformly over the exposed surface of the concrete, in the case of the cylinder, the difference in temperature amounted to several degrees at the most remote distance from the lamps. However, since only a comparatively small part of the cylinder was considered in the calculations

and the section was well within the range of uniform heat, the error due to uneven heating can be disregarded.

It is impossible to come to any definite conclusions as to the cause of the variation in results in each particular case, but it is probable that the greatest source of variation is in the temperature-distance curves. Any slight variation from the true position would cause an error in the temperature gradient. However, most of the errors of measurement, as well as the errors of plotting are eliminated by determining the value of the thermal conductivity from a mean curve for all the calculated values of k plotted as ordinates with the corresponding temperature gradients as abscissas, as shown on pages 31 and 32.

CONCLUSION.

On account of the lack of time for preparation of any elaborate apparatus, the method of conducting the experiments as described above was chosen for its simplicity of construction of apparatus and ease of controlling temperatures. The concrete was proportioned by weight and there was probably some difference in the consistency of the different mixtures. This would cause only slight variations in the specific heat and in the thermal conductivity. A concrete with a small percentage of voids will undoubtedly have a higher thermal conductivity than one with a large percentage of voids.

From a study of the results given both in the tables and graphs, it will be seen that although there is a rather large range of values, the larger part of the values obtained have only a small variation from the mean. The curves show rather

better than the tabulated results, that the value of the thermal conductivity is a constant for ordinary atmospheric temperatures.

Beam encased - ready for test.

Cylinder No. 2.

Beam Heater.

Cylinder No. 1. encased ready for test.

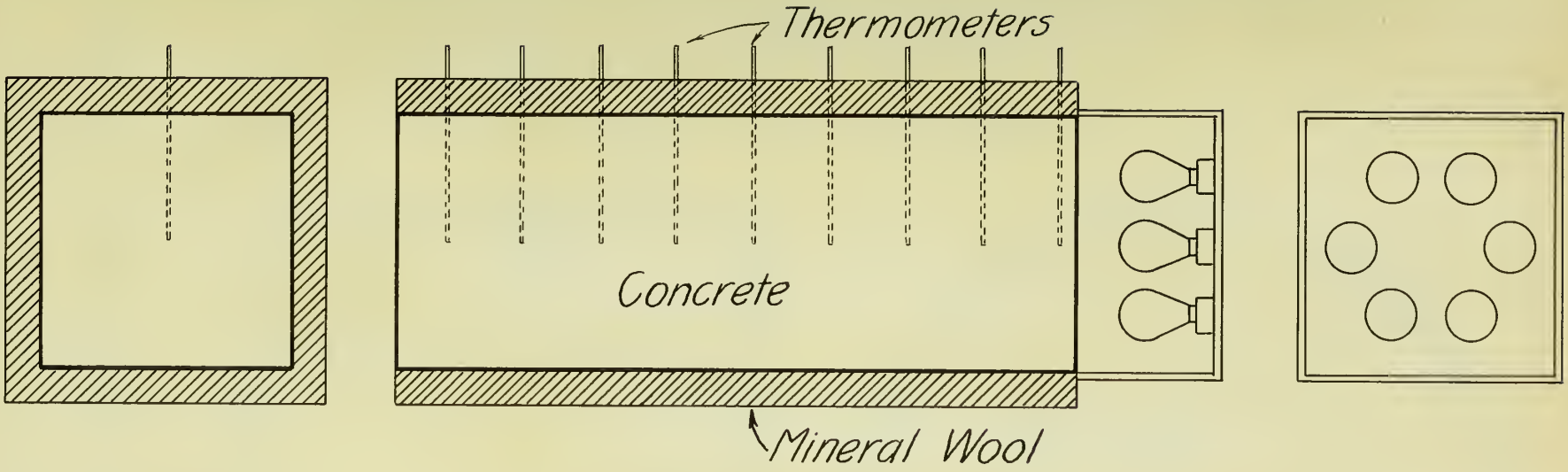


Diagram Showing Method of Heating Beam.

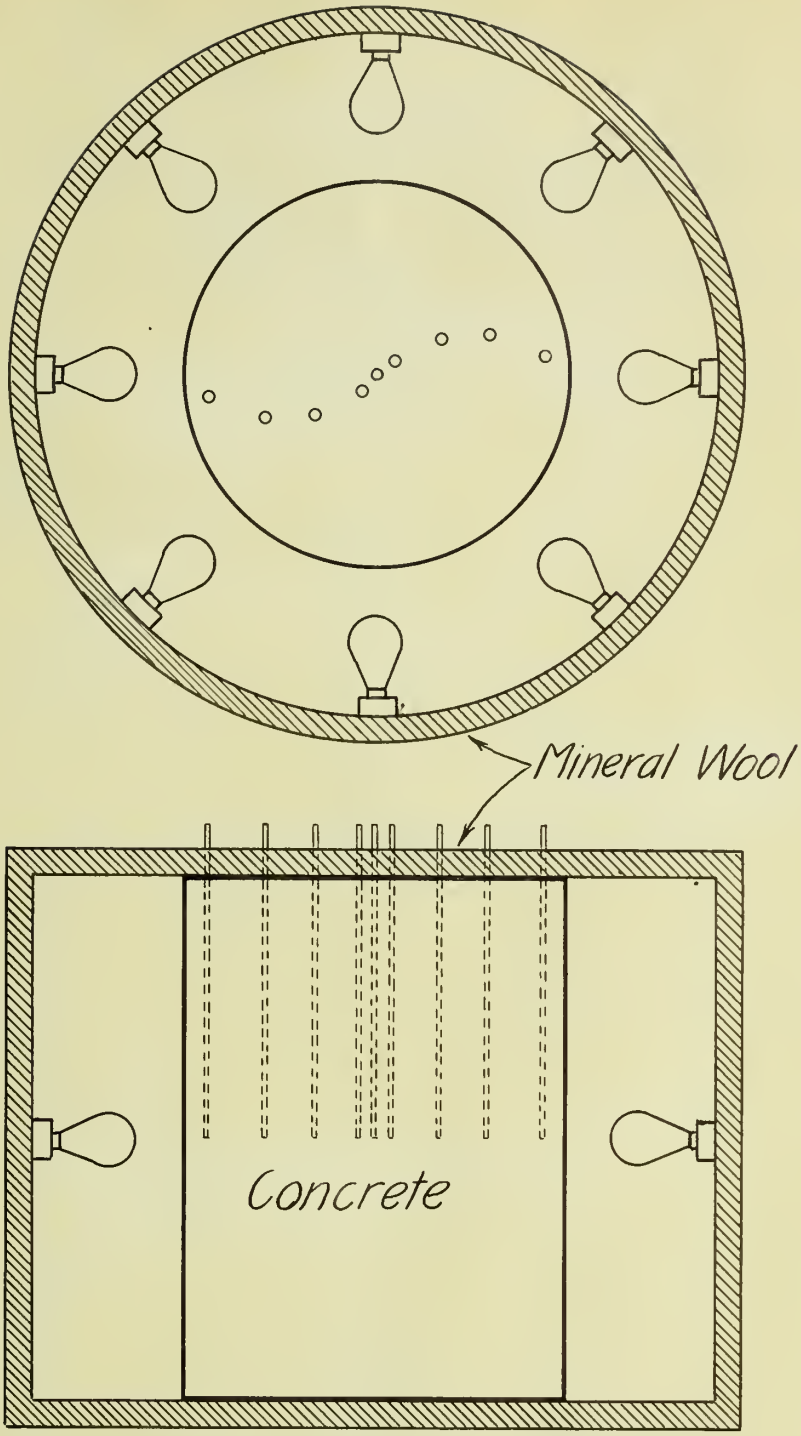


Diagram Showing Method of Heating Cylinders.

TABLE 1.

TEMPERATURES AT CORRESPONDING DISTANCES FROM HEATED SURFACE OF CONCRETE BEAM.

Dist.cm.	2.54	12.7	22.9	33.0	43.2	53.4	63.5	73.7	83.8
Time	Temperature - Degrees C.								
6:35	22.2	22.5	22.4	22.3	22.5	22.0	21.9	22.1	22.0
7:15	33.0	23.1	22.4	22.3	22.5	22.0	21.9	22.1	22.0
7:35	36.7	24.1	22.5	22.3	22.5	22.0	21.9	22.1	22.0
8:05	41.9	26.2	23.0	22.5	22.5	22.1	21.9	22.1	22.0
8:35	45.0	28.3	23.3	22.5	22.6	22.0	21.9	22.1	22.0
9:05	48.2	30.4	24.0	22.8	22.6	22.0	21.9	22.1	22.0
10:05	53.2	34.1	25.6	23.0	22.6	22.0	21.9	22.1	22.0
11:05	57.0	37.9	27.8	24.0	22.9	22.0	21.9	22.1	22.0
12:05	60.5	40.6	29.5	25.0	23.2	22.0	21.9	22.1	22.0
1:05	62.9	43.1	31.3	26.0	23.7	22.3	22.0	22.1	22.0
2:05	65.0	45.4	33.0	27.0	24.1	22.5	22.0	22.1	22.0
3:05	67.1	47.5	34.9	28.2	25.0	23.0	22.2	22.1	22.0
4:05	68.7	49.1	36.2	29.1	25.5	23.0	22.2	22.1	22.0
5:05	70.6	50.9	37.5	30.4	26.2	23.3	22.3	22.1	22.0
7:20	73.1	54.0	40.5	32.6	27.8	24.3	22.9	22.2	22.0
9:20	75.0	56.2	42.6	34.1	29.0	25.3	23.4	22.6	22.1
10:20	76.1	57.3	43.8	35.3	29.6	25.8	23.8	22.9	22.2
12:20	78.8	59.3	45.2	36.6	30.8	26.4	24.4	23.2	22.5
2:20	80.8	61.5	47.5	38.5	32.4	27.5	25.4	23.8	23.2
3:50	82.0	63.1	48.9	39.8	33.2	28.3	25.9	24.2	23.6

TABLE 2.

TEMPERATURES AT CORRESPONDING DISTANCES FROM HEATED SURFACE OF CONCRETE CYLINDER NO. 1.

TEST NO. 1.

Dist.cm.	2.68	7.93	12.78	17.63	19.84
Time	Temperature - Degrees C.				
8:30	21.8	21.6	21.4	21.4	21.8
8:45	24.6	21.8	21.4	21.4	21.8
9:00	27.2	22.9	21.7	21.4	21.8
9:15	29.7	24.3	22.4	21.8	22.1
9:30	31.6	25.8	23.3	22.3	22.7
9:45	33.8	27.2	24.4	23.4	23.4
10:00	34.9	28.7	25.8	24.4	24.7

TABLE 3.

TEMPERATURES AT CORRESPONDING DISTANCES FROM HEATED SURFACE

OF CONCRETE CYLINDER NO. 1.

TEST NO. 2.

Dist.cm.	2.86	7.93	12.78	17.63	19.84
Time.	Temperature - Degrees C.				
1:50	19.6	19.4	19.3	19.1	19.4
2:00	20.7	19.4	19.3	19.1	19.4
2:10	22.9	19.7	19.3	19.1	19.4
2:20	24.8	20.5	19.5	19.1	19.4
2:30	26.5	21.3	19.8	19.2	19.5
2:40	29.0	22.6	20.5	19.6	20.0
3:00	32.2	25.1	22.0	20.8	21.0
3:20	35.6	27.7	24.0	22.3	22.3
3:40	38.5	30.3	26.2	23.7	24.1
4:00	41.2	32.9	28.4	26.3	26.3
4:20	45.0	35.5	31.7	28.5	28.5
4:45	47.9	38.6	33.8	31.3	31.2
5:00	49.0	40.6	35.7	33.3	33.3

TABLE 4.

TEMPERATURES AT CORRESPONDING DISTANCES FROM HEATED SURFACE OF CONCRETE CYLINDER NO.1.

TEST NO.3.

Dist.cm.	2.86	7.93	12.78	17.63	19.84
Time	Temperatures - Degrees C.				
8:00	20.4	20.2	20.0	20.0	20.4
8:15	22.9	20.2	20.0	20.0	20.4
8:30	26.5	21.4	20.3	20.0	20.4
8:45	29.4	23.0	21.0	20.3	20.7
9:00	32.3	24.8	22.1	21.0	21.1
9:15	34.3	26.7	23.6	22.0	22.0
9:30	36.4	28.6	24.9	23.1	23.2
9:45	38.5	30.7	26.6	24.6	24.8
10:00	41.5	32.4	28.3	26.1	26.1
10:20	44.2	35.1	30.6	28.3	28.3
10:40	46.8	37.6	33.1	30.8	30.8
11:00	49.2	40.0	35.5	33.1	33.1
11:20	51.4	42.3	37.9	35.5	35.5
11:40	53.4	44.6	40.0	37.7	37.8
11:52	55.1	46.1	41.6	39.1	39.2

TABLE 5.

TEMPERATURES AT CORRESPONDING DISTANCES FROM HEATED SURFACE OF CONCRETE CYLINDER NO.2.

TEST NO.1.

Dist.cm.	2.93	4.84	7.38	12.39	19.05
Time	Temperatures - Degrees C.				
2:15	20.3	20.1	20.0	19.7	20.0
2:30	22.7	21.2	20.2	19.7	20.0
2:45	27.3	24.5	22.2	20.4	20.1
3:00	30.6	27.2	24.1	21.3	20.9
3:15	33.1	29.6	26.4	22.9	21.5
3:30	35.9	32.3	28.6	24.6	23.0
3:45	38.7	35.0	30.9	26.3	24.2
4:00	41.2	37.1	33.2	28.2	26.0
4:15	43.5	39.8	35.5	30.5	28.0

TABLE 6.

DATA AND RESULTS OF SPECIFIC HEAT TESTS ON THE CONCRETE.

BEAM CONCRETE.

No. of Test.	Wt. of Water in grams	Wt. of Concrete in grams	Temperatures in Degrees C.			Specific Heat in Calories
			Initial Water	Initial Concrete	Final Mixture	
1	279.5	195.6	24.7	66.2	30.1	0.213
2	294.2	209.9	24.7	65.5	29.9	.205
3	299.3	199.0	25.2	67.0	30.2	.204
4	288.9	208.5	24.7	68.2	30.4	.208
5	296.7	195.4	24.7	65.0	29.8	.220
					Average	0.210

CYLINDER CONCRETE.

1	290.6	196.0	22.4	62.6	27.4	0.210
2	287.6	234.7	24.1	66.1	29.7	.189
3	314.4	203.2	24.3	62.0	28.5	.189
4	314.9	216.0	24.3	64.2	29.2	.204
5	336.1	219.5	24.2	66.6	28.7	.181
					Average	0.194

TABLE 7.

VALUES OF THE THERMAL CONDUCTIVITY (k) OBTAINED FROM TEST ON CONCRETE BEAM.

Ref. No.*	Distance from Heated Surface in Centimeters. 5		10		15		20	
	Tan B†	k	Tan B	k	Tan B	k	Tan B	k
1	1.762	.00150	1.680	.00140	1.260	.00160	1.080	.00160
2	1.797	.00167	1.635	.00168	1.311	.00173	1.000	.00186
3	1.859	.00166	1.666	.00154	1.300	.00158	0.983	.00168
4	1.902	.00139	1.582	.00133	1.237	.00134	0.956	.00136
5	1.896	.00199	1.568	.00205	1.222	.00220	0.909	.00240
6	1.907	.00173	1.572	.00162	1.190	.00165	0.870	.00173
7	1.937	.00177	1.560	.00173	1.111	.00190	0.846	.00178
8	1.912	.00186	1.477	.00174	1.032	.00180	0.778	.00171
9	1.890	.00230	1.340	.00237	0.919	.00242	0.640	.00230
10	1.841	.00196	1.188	.00203	0.768	.00188	0.444	.00175
11	1.725	.00220	1.009	.00221	0.568	.00218	0.312	.00260
	25		30		35		40	
1	0.908	.00158	0.682	.00170	0.507	.00200	0.433	.00190
2	0.833	.00183	0.629	.00195	0.496	.00202	0.408	.00185
3	0.763	.00172	0.582	.00164	0.448	.00139	0.327	.00115
4	0.746	.00125	0.566	.00117	0.379	.00103	0.282	.00077
5	0.709	.00234	0.524	.00240	0.330	.00284	0.251	.00259
6	0.808	.00128	0.433	.00157	0.296	.00161	0.220	.00138
7	0.624	.00171	0.344	.00193	0.243	.00167	0.171	.00127

† Note 1. Values of Temperature Gradient (Tan B) were scaled from the Temperature-Distance Curves.

* Note 2. Reference Nos. correspond to time intervals in the order shown in the tables on page 15.

TABLE 8.

VALUES OF THE THERMAL CONDUCTIVITY (k) OBTAINED FROM TEST ON CONCRETE CYLINDER NO.1.

TEST NO.1.

Distance from Heated Surface in Centimeters.								
Ref. No.*	5		10		15		20	
	Tan B†	k	Tan B	k	Tan B	k	Tan B	k
1	1.292	.00176	0.990	.00187	0.562	.00240	0.332	.00272
2	1.250	.00152	0.926	.00152	0.510	.00205	0.274	.00262
3	1.106	.00162	0.816	.00156	0.402	.00219	0.208	.00269
4	0.940	.00185	0.682	.00160	0.292	.00220	0.125	.00303
5	0.692	.00160	0.452	.00170	0.120	.00120		

†* See Notes 1 and 2 on page 21.

TABLE 9.

VALUES OF THE THERMAL CONDUCTIVITY (k) OBTAINED FROM TEST ON CONCRETE CYLINDER NO.1.

TEST NO.2.

Distance from Heated Surface in Centimeters.								
Ref. No.*	5		10		15		20	
	Tan B†	k	Tan B	k	Tan B	k	Tan B	k
1	1.785	.00170	1.377	.00188	0.946	.00210	0.688	.00206
2	1.915	.00137	1.390	.00145	0.925	.00158	0.666	.00149
3	1.797	.00173	1.340	.00187	0.839	.00242	0.630	.00237
4	1.610	.00178	1.250	.00185	0.800	.00221	0.594	.00220
5	1.546	.00176	1.170	.00186	0.800	.00200	0.562	.00194
6	1.458	.00183	1.020	.00193	0.680	.00205	0.470	.00204
7	1.352	.00197	0.875	.00216	0.528	.00236	0.340	.00215

†* See Notes 1 and 2 on page 21.

TABLE 10.

VALUES OF THE THERMAL CONDUCTIVITY (k) OBTAINED FROM TEST ON CONCRETE CYLINDER NO.1.

TEST NO.3.

Distance from Heated Surface in Centimeters.								
Ref. No.*	5		10		15		20	
	Tan B†	k	Tan B	k	Tan B	k	Tan B	k
1	1.767	.00167	1.290	.00184	0.959	.00192	0.658	.00199
2	1.800	.00143	1.310	.00164	0.900	.00188	0.578	.00216
3	1.845	.00145	1.320	.00173	0.875	.00210	0.534	.00254
4	1.847	.00156	1.335	.00174	0.897	.00199	0.535	.00242
5	1.850	.00153	1.327	.00178	0.890	.00210	0.536	.00264
6	1.842	.00155	1.302	.00177	0.851	.00206	0.517	.00240
7	1.192	.00225	1.100	.00197	0.835	.00212	0.493	.00266
8	1.530	.00198	1.040	.00226	1.344	.00125	0.504	.00223
9	1.492	.00178	1.097	.00176	1.228	.00108	0.489	.00185
10	1.530	.00157	0.941	.00194	0.573	.00230	0.415	.00220

†* See Notes 1 and 2 on page 21.

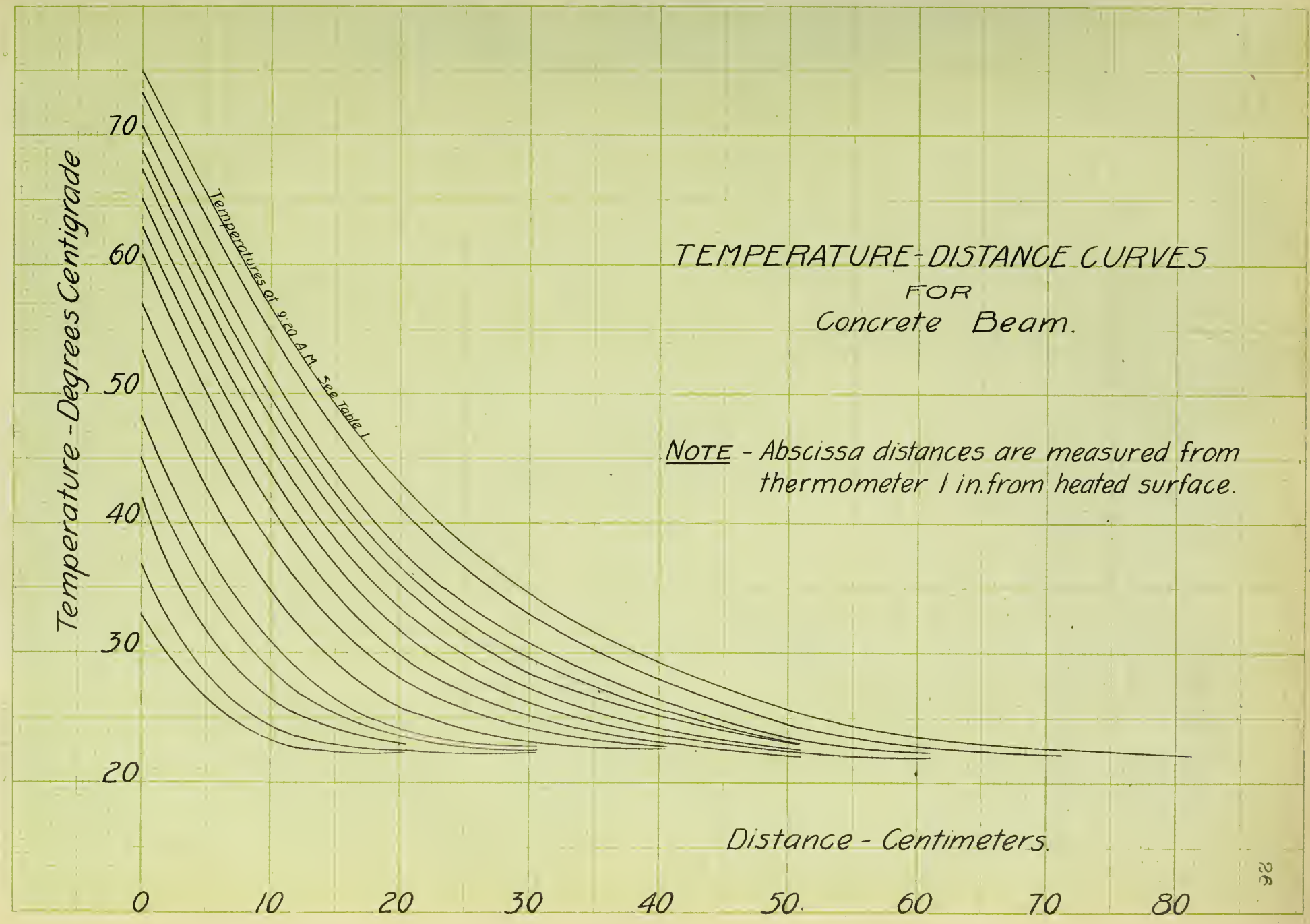
TABLE 11.

VALUES OF THE THERMAL CONDUCTIVITY (k) OBTAINED FROM TEST ON CONCRETE CYLINDER NO.2.

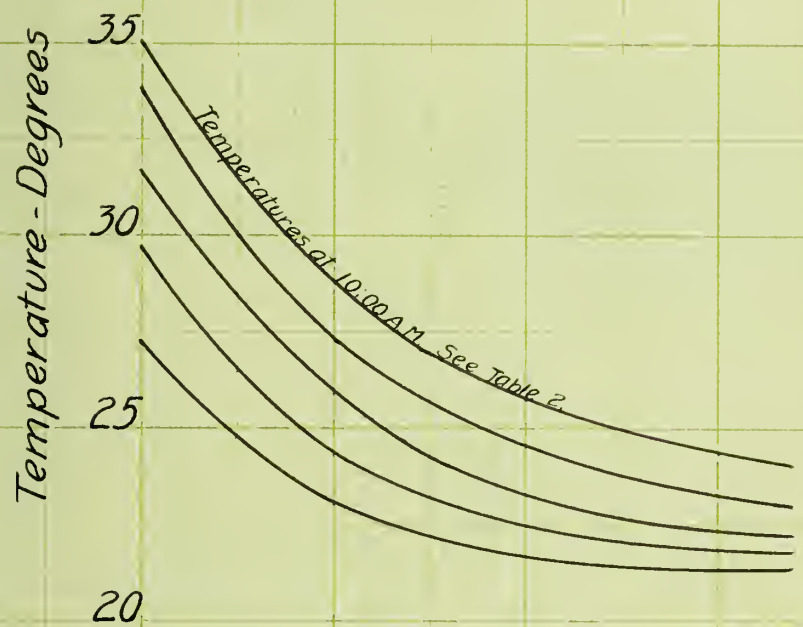
TEST NO.1.

Distance from Heated Surface in Centimeters.								
Ref. No.*	5		10		15		20	
	Tan P†	k	Tan P	k	Tan P	k	Tan P	k
1	1.782	.00204	1.353	.00215	0.886	.00252	0.496	.00328
2	1.750	.00178	1.271	.00191	0.833	.00230	0.468	.00312
3	1.678	.00174	1.170	.00181	0.759	.00206	0.423	.00248
4	1.547	.00185	1.029	.00208	0.641	.00252	0.371	.00316

†* See Notes 1 and 2 on page 21.


TEMPERATURE-DISTANCE CURVES
FOR
Concrete Beam.
NOTE - Abscissa distances are measured from thermometer 1 in. from heated surface.
Temperatures at 9:30 A.M. See Table 1.
Temperature - Degrees Centigrade
70
60
50
40
30
20
Distance - Centimeters.
0
10
20
30
40
50
60
70
80

TEMPERATURE - DISTANCE CURVE
FOR
Concrete Cylinder No.1.
Test No.1.

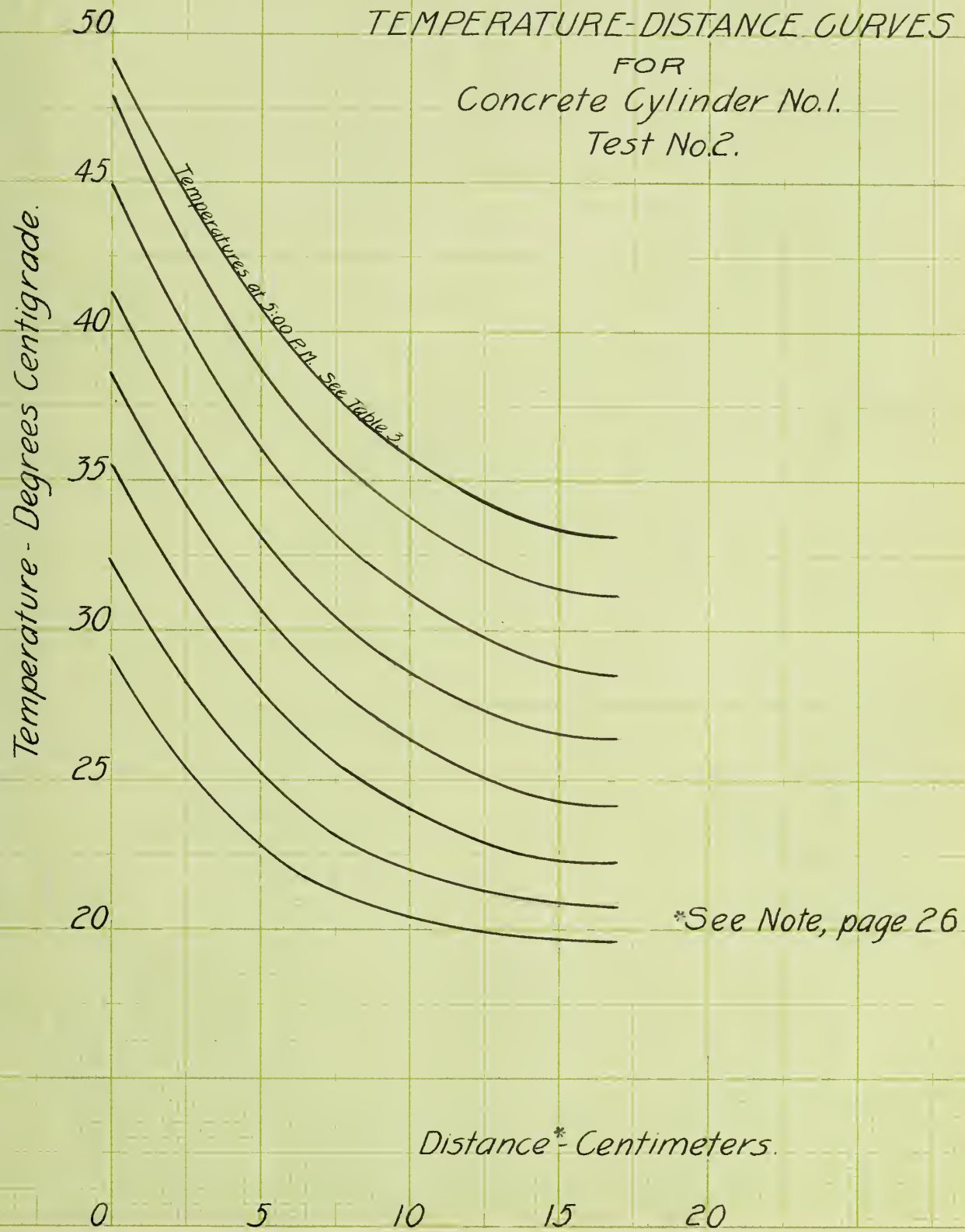


*See Note, page 26

Distance* Centimeters.

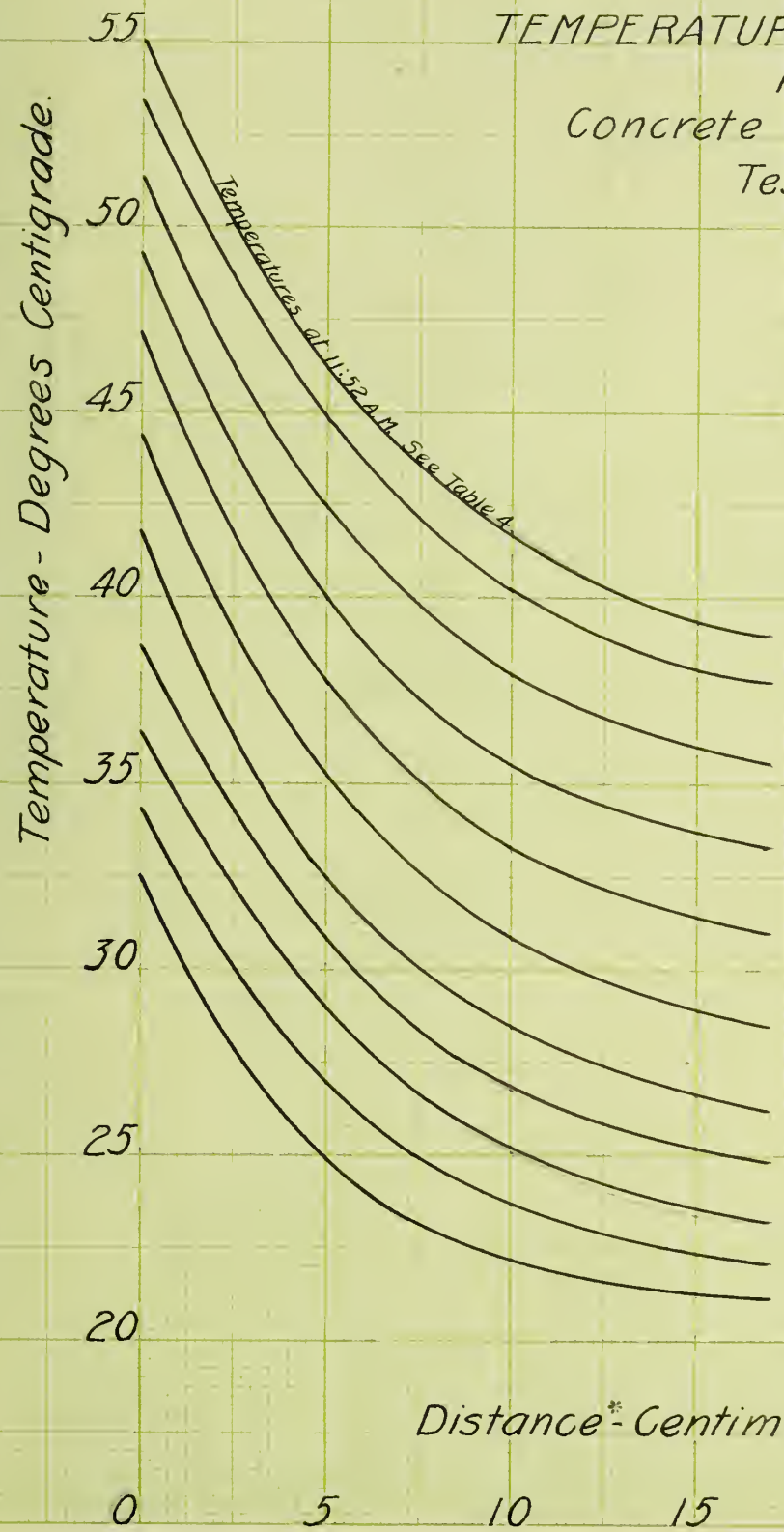
0 5 10 15 20

TEMPERATURE-DISTANCE CURVES
FOR
Concrete Cylinder No.1.
Test No.2.



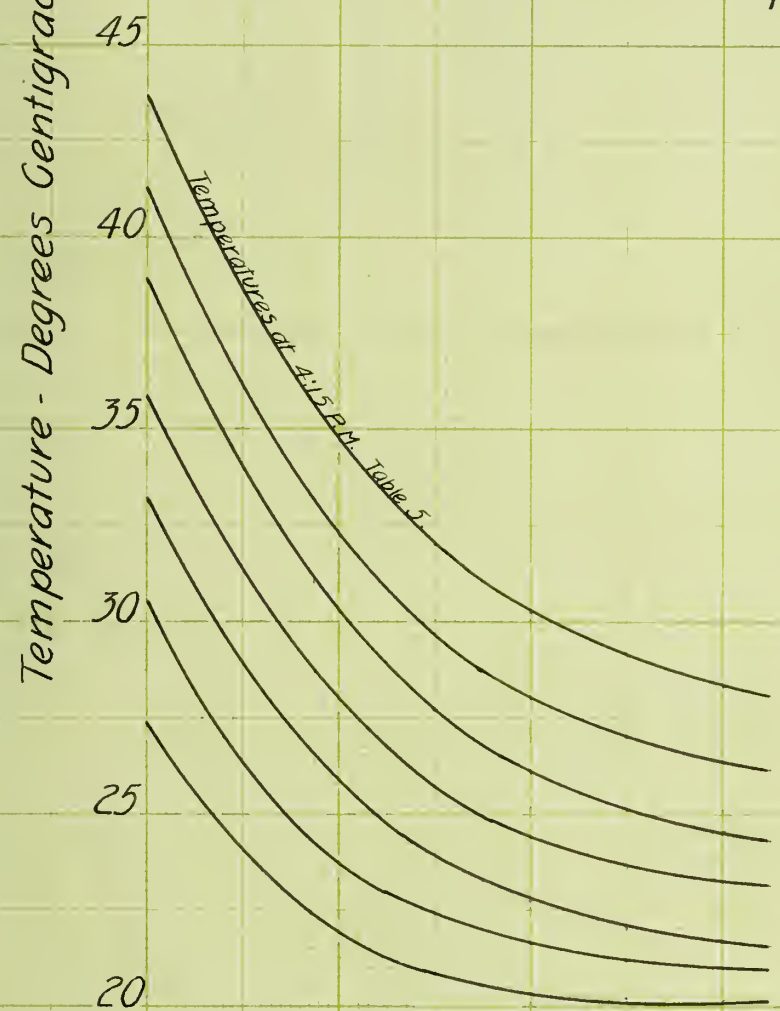
*See Note, page 26

TEMPERATURE-DISTANCE CURVES
FOR
Concrete Cylinder No. 1.
Test No. 3.



*See Note, page 26.

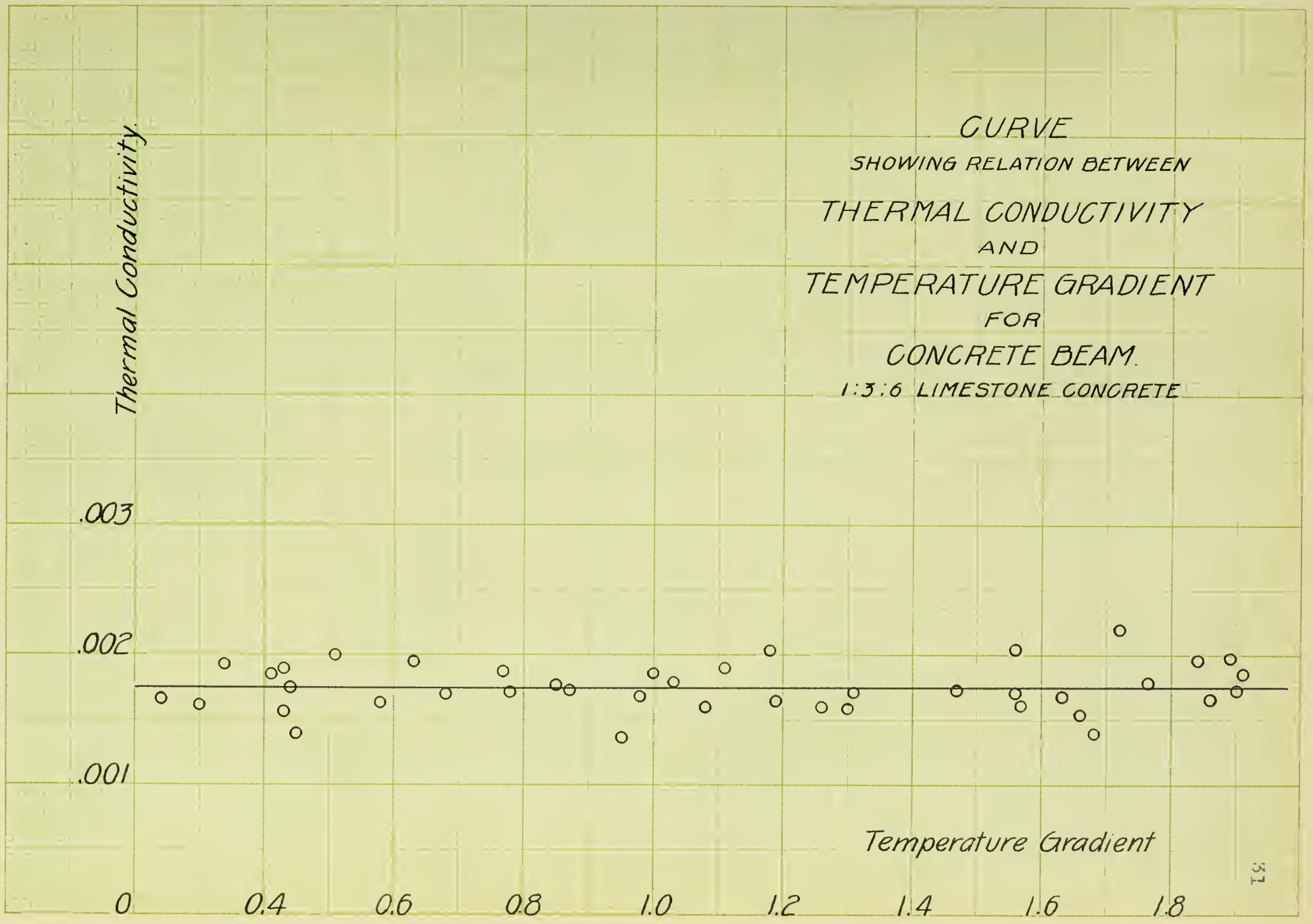
TEMPERATURE-DISTANCE CURVES.
FOR
Concrete Cylinder No.2.
Test No.1.

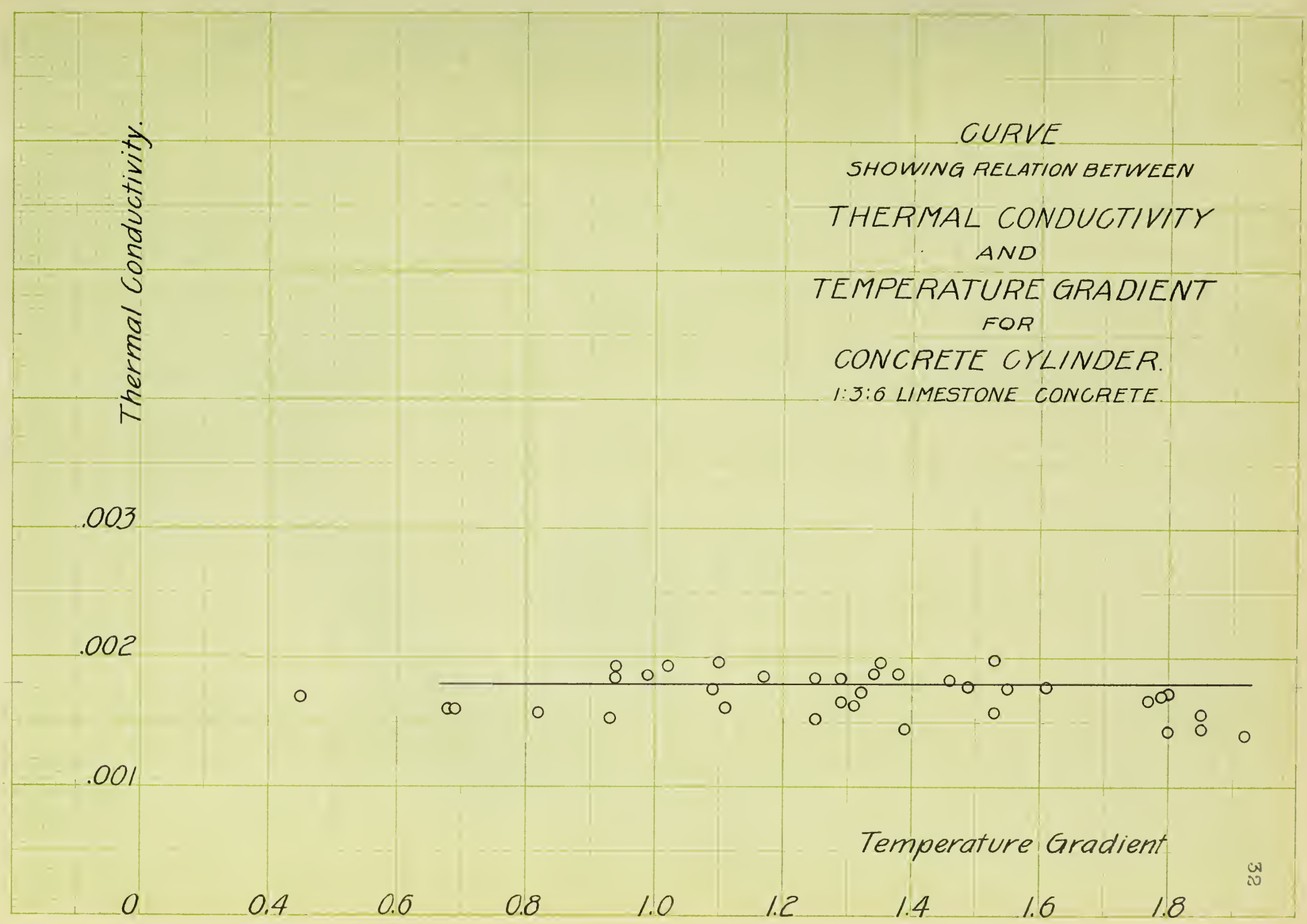


*See Note, page 26.

Distance* - Centimeters.

0 5 10 15 20


CURVE
SHOWING RELATION BETWEEN
THERMAL CONDUCTIVITY
AND
TEMPERATURE GRADIENT
FOR
CONCRETE BEAM.
1:3:6 LIMESTONE CONCRETE
Thermal Conductivity.
.003
.002
.001
Temperature Gradient
0
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
31


CURVE
SHOWING RELATION BETWEEN
THERMAL CONDUCTIVITY
AND
TEMPERATURE GRADIENT
FOR
CONCRETE CYLINDER.
1:3:6 LIMESTONE CONCRETE.
Thermal Conductivity.
.003
.002
.001
0
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
Temperature Gradient
32

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